

The LLNL Accelerator Mass Spectrometry System for Biochemical ^{14}C -Measurements

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The LLNL accelerator mass spectrometry system for biochemical ^{14}C -measurements

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Abstract

We report on recent improvements made to our 1 MV accelerator mass spectrometry system that is dedicated to ^{14}C quantification of biochemical samples. Increased vacuum pumping capacity near the high voltage terminal has resulted in a 2-fold reduction of system backgrounds to 0.04 amol ^{14}C /mg carbon. Carbon ion transmission through the accelerator has also improved a few percent. We have also developed tritium measurement capability on this spectrometer. The $^3\text{H}/^1\text{H}$ isotopic ratio of a milligram-sized processed tap water sample has been measured at $4 \pm 1 \times 10^{-16}$ ($430 \pm 110 \mu\text{Bq/mg H}$). Measurement throughput for a typical biochemical ^3H sample is estimated to be ~10 minutes/sample.

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1. Introduction

Accelerator mass spectrometry (AMS) has been used in the biosciences to provide highly sensitive and precise ^{14}C quantification at environmentally relevant doses[1-5]. The development of lower acceleration voltages [6,7] for detection of specific isotopes leads to the possibility of spectrometers tailored to particular AMS applications. In the biosciences, precision can be relaxed to enable high sample measurement throughput. High sensitivity, however, must be maintained to allow for the measurement of very small samples. Specifically, we require for the measurement of at least 300 samples per day containing 1 mg or less carbon, at 3-5% precision with reproducible background count rates equivalent to <1 attomole $^{14}\text{C}/\text{mg}$ carbon.

Tritium is also a widely used isotope tracer in biochemical experiments. Many compounds that cannot be easily synthesized with a ^{14}C label can be tagged with ^3H . AMS provides a factor of 1000 improvement in tritium sensitivity on milligram-sized samples with much higher throughput over traditional decay measurement techniques[8].

We recently reported on the characterization of a 1 MV AMS spectrometer constructed at the Lawrence Livermore National Laboratory's Center for Accelerator Mass

Spectrometry which is dedicated to biochemical ^{14}C measurements[9]. This spectrometer meets or exceeds our requirements as outlined above. This paper describes the improvements we have recently made to our spectrometer in the measurement of ^{14}C and shows some initial results in the development of ^3H measurement capability at $<1\text{ MV}$.

2. Experimental

A photograph of the spectrometer is shown in Fig. 1. A copy of the LLNL high-output cesium-sputter source is used to generate negative ions from solid targets[10]. After energy and momentum analysis, ions are injected into the high voltage terminal of a National Electrostatic Corporation 3SDH-1 1MV Pelletron® tandem accelerator. Charge-exchange and molecular ion dissociation processes occur in a long cell, filled with diffuse argon gas located at the center of the accelerator. After subsequent acceleration, transmitted ions are then momentum-analyzed followed by an energy-analysis before impinging on a silicon surface barrier detector. The spectrometer is housed in a 44 m^2 room adjacent to and is $\sim 20\%$ the size of the LLNL 10MV FN tandem accelerator[11]. Details of the spectrometer are provided elsewhere[9,12].

Recently, we replaced the thermocouple ion pressure gauge to provide for a more stable and consistent monitor of the argon gas density within the stripper canal. We added a second 220 l/sec turbomolecular vacuum pump to the beam line region between the high voltage terminal of the accelerator and the analysis magnet. We also placed a collimator at the entrance to the analysis magnet to limit the amount of residual argon gas reaching the magnetic field region of the magnet. Additionally, we replaced the beam profile monitor located in this region with an insertable Faraday cup.

These changes necessitated the recharacterization of the spectrometer to maximize sample throughput and precision and to minimize backgrounds. This work required that the gas pressure within the stripper canal be adjusted while observing the count rate within the ^{14}C gate of the detector. For a ^{14}C -free carbonaceous sample, this lowest count rate ultimately determines the sensitivity of the spectrometer. The gas pressure required to reach this limit also determines the effective transmission through the accelerator given that the most efficient coupling of the ion source to the accelerator has been achieved.

While the spectrometer was originally designed to quantitate ^{14}C , we have begun to explore ^3H measurement capabilities. Solid TiH_2 targets for ^3H -AMS measurement were prepared from 1-10 μl liquid water samples[13]. The large relative mass difference between hydrogen and tritium precludes us from using electrostatic isotope switching for ions with energy >15 keV. The ion source is designed to extract ions at 40 kV and operation at potentials significantly less than is inefficient. Instead, the magnetic field of the injection magnet is cycled to permit the sequential transmission of the two 40 keV isotopes. Tritium is measured for 10 seconds with the silicon surface barrier detector located at the end to the spectrometer while hydrogen is measured for 5 seconds at an off-axis Faraday cup located at the entrance to the accelerator. Changing the magnetic field requires approximately 20 seconds.

3. Results and discussion

Fig. 2 shows a plot of carbon isotope ratios measured at different argon gas pressures for graphitized coal samples. In this spectrum, all events falling within the appropriate hardware and software gates are recorded as $^{14}\text{C}^+$. Each data point represents an average of

at least 3 measurements of 3 different samples with the error bars indicating the 1-sigma standard deviation about the mean. The average background between 41 and 47 mTorr is 0.0041 Modern (0.40 attomoles ^{14}C /mg carbon). As the gas pressure increases, ion scattering in the gas canal and beam line tubes increases, which results in the higher background levels observed in the detector. No attempt was made to differentiate sources contributing to detector signal when tuned to ^{14}C . Similarly-prepared coal samples are <0.002 Modern when measured on the 10 MV FN tandem, indicating that about 1/2 of the counts are still scattered ions or contaminants.

This level in system background represents a factor of two improvement in sensitivity from earlier work[9]. Also, about 10 mTorr less gas pressure is required to adequately destroy interfering molecules. It is possible that the argon gas is better constrained within the beam line by the additional vacuum pump and limiting aperture. This allows for the molecules to be dissociated in a shorter path, thus limiting ion scattering. We have seen an increase in the carbon ion transmission through the accelerator to approximately 36%.

Fig. 3 shows a comparison of hydrogen isotope ratios of tritium standards measured by AMS from that determined from LSC. The error bars represent the 1-sigma standard deviation about the average of at least three measurements of two replicate samples in the AMS case and three measurements of a single standard in the LSC case. From a calibration curve generated from the data, the isotope ratio of a processed tap water blank was determined to be $4 \pm 1 \times 10^{-16} \text{ }^3\text{H}/^1\text{H}$ ($430 \pm 110 \text{ } \mu\text{Bq } ^3\text{H}/\text{mg H}$).

Sample throughput of a typical 1 mg-sized biomedical sample with a 10^{-14} T/H ratio is estimated to be 10 minutes/sample based on observed $^1\text{H}^-$ ion currents of 150 μA . This is

to obtain 5% precision based on counting statistics with at least 3 replicate measurements. A similarly-sized sample would require more than 10 hours of decay counting to obtain this precision in the counting statistics of a single measurement, assuming no background and 100% detection efficiency. Tandem accelerating voltage and Ar stripper gas pressure were set to 520 kV and 45 mTorr, which is identical to that used for the quantitation of carbon isotope ratios. Further work is continuing to ascertain if these are the preferred operating parameters for hydrogen isotope ratio quantitation.

4. Conclusions

Routine operation of the spectrometer for biochemical ^{14}C measurements began in April 2001. On average, 650 samples are measured each month in a 2-3 days per week operation. Table 1 summarizes the performance and operation of the spectrometer. Tritium quantitation development, as well as other AMS measurement techniques are conducted while the spectrometer is not busy with routine measurements.

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Figure Captions

Fig. 1. Photograph of the LLNL AMS system for biochemical ^{14}C measurements.

Fig. 2. Carbon isotope ratios measured as a function of argon gas pressure in the molecular dissociation cell. Tandem accelerating voltage of 520 kV was applied during these tests. Error bars, when not shown, are smaller than the data point.

Fig. 3. Tritium standard curve with the AMS measured hydrogen isotope ratio as the abscissa and the LSC-determined ratio as the ordinate.



Figure 1

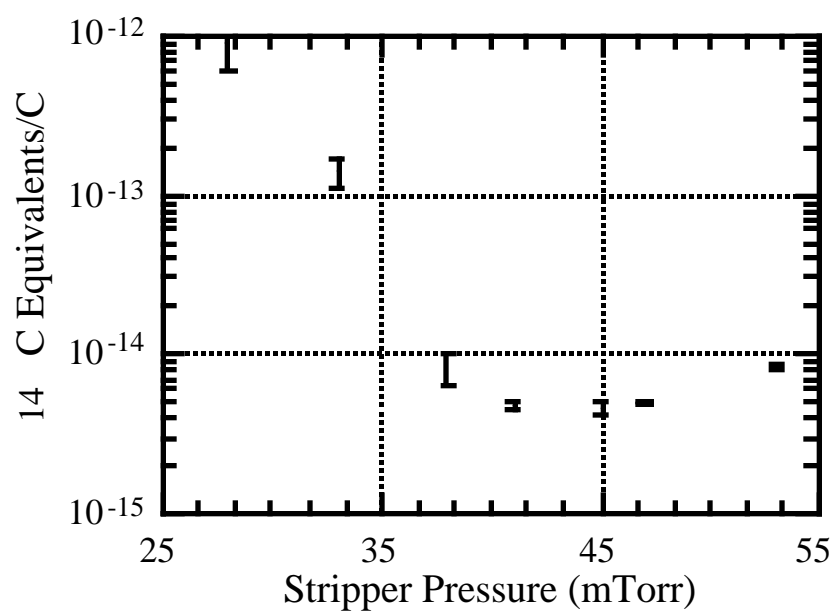


Figure 2

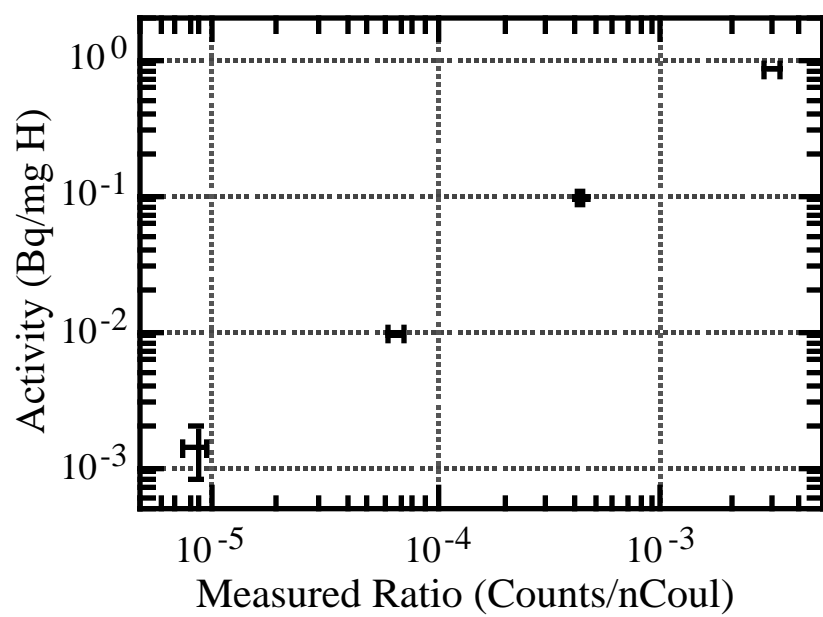


Figure 3

Table 1.

Summary performance and operating parameters for the 1-MV spectrometer for the measurement of ^{14}C .

Sample Performance	
Sensitivity	0.004 Modern (0.4 amol ^{14}C /mg carbon)
Dynamic range	4-5 orders of magnitude
Sample throughput	105 samples/8 h (average)
Precision	3%
Operation	
Ion source	64 sample cesium sputter
Extraction voltage	40 kV
Source output	300 μA (typical)
Analyzed low-energy ions	$^{12}\text{C}^-$ (200 μA typical)
Accelerator voltage	520 kV
Ion stripping gas pressure	~45 mTorr argon
Analyzed stable ions	1.08 MeV $^{13}\text{C}^+$ (800 nA typical)
Analyzed rare ions	1.08 MeV $^{14}\text{C}^+$